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Why and How Physically-based model are able to model Emergent Crowd Behaviors?

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Abstract

This paper has been written as a position paper on the concepts of emergence, individual / collective paradox, from both philosophical and experimental point of view. It presents successively:

(1) Some sociological and philosophical issues related to collective emergent behaviors

It compares the main sociological and philosophical points of view about what do collective phenomena and emergent property mean. It analyses the global incidence of such point of view on the modeling concepts; it distinguishes the different types of collective features, between collective non-deliberative action and common action with deliberative action or explicit symbolic common goal.

(2) A non-conventional point of view of physical particle modeling as a cellular automata systems:

It starts from some philosophical issues on physical modeling. It shows why physical particle modeling systems are dynamic cellular automata, called Newtonian Networks. It compares them with others types of cellular networked automata, neural networks and agent based networks.

(3) A proposition of a generic physical particle model for emergent collective phenomena

It starts with the specification of the dynamic emergent features characterizing a crowd in the sense of a class of phenomena exhibited by a set of individuals. It presents a minimal and generic particle physical model and its application to human crowds' behaviors.

(4) It shows that this model is able to render the main expected figures of non-deliberative emergent collective phenomena as those that define crowd behaviors.

Keywords:

Physical modeling, emergent behavior, collective phenomena, particle modeling, Crowd dynamics

1 Introduction

Usually, emergent collective behaviors are associated to behaviors of living beings and it is commonly considered that the best types of models and concepts adapted to render them are behavioral models are those based on agents concepts, developed by artificial intelligence, or artificial life.

Conversely, physical models or physically-based models are usually restricted to the modeling and simulation of non-living nature, or animation of non-living behaviors.

In this paper, we would like to demonstrate that this association between a type of dynamic phenomenon and a type of model is an a-priori categorization based on two main misunderstanding: misunderstanding of what is "a crowd", and misunderstanding of what is physical model".

To achieve this theoretical and pragmatic aim, we will presents successively :

(1) Some sociological and philosophical issues related to collective emergent behaviors by comparing the main sociological and philosophical points of view about what do collective phenomena and emergent property mean. We will present then the global incidence of such point of view on the modeling concepts. We will analyze the different types of collective features, distinguishing between collection non-deliberative action and common action with deliberative activity or explicit symbolic common goal.

(2) A non-conventional point of view of physical particle modeling as a dynamic cellular automata systems derived from philosophical issues on physical modeling. We will define physical particle modeling systems as dynamic cellular automata. We called them Newtonian Networks and we will compare them with others types of cellular networked automata, neural networks and agent based networks.

(3) A proposition of a generic physical particle model for emergent collective phenomena and its application to human crowds' behaviors. We will start with the specification of the dynamic emergent features characterizing a crowd in the sense of a class of phenomena exhibited by a set of individuals. We will design a minimal and generic particle physical model and we analyze the results obtained from simulations of this model.

(4) We will show that this model is able to render the main figures of non-deliberative *emergent collective phenomena as those that* define crowd behaviors.

2 Sociological and philosophical issues

The three terms, « collective », « emergent », and « phenomenon », as well as their association, rise some epistemological and linguistic problems. We will examine here some relevant and differentiating aspects which allow to clarify the properties of the modeling system we can select and the types of patterns we have to render by means of the simulation of the selected types of models.

2.1 About the terms "collective" and "emergent"

Two theories are generally opposed in from what the "collective phenomena" are emerging. The first one is Durkheim's theory [Durkheim 1958, 1917] by which the collective is defining the individuals. The individuals encode specific collective behaviors through collective representations and cultural rules. The capabilities to exhibit or the follow collective behaviors seem "programmed" as specific functionalities inside the individuals. Conversely, the modernism based on the prerequisites of the individual rather than the collective, assume that *the collective is built from the individual* properties. In each both case, the relation between the individual and the collective remain unresolved. In both cases, the "sorite" paradigm remains not solved : how the property P, can appear from an element that has not the property P to from a set of these elements? Symmetrically, how a property P can disappears from set of elements to the element that has not the property P?

This unsolved paradigm is illustrated by the common paradox : from what number of grains of rice we obtain a pile of rice, by adding grains? And conversely, to lead to the Durkheim's point of view, from what number of grains of rice, a set of grains of rice is no longer a pile of rice, by removing grains.

The notion of *emergence* is central to this problem. According to Taylor (Tay92), emergence is a process in which a collection of interacting units acquires qualitatively new properties that cannot be reduced to a simple superposition of individual contributions. The literary "sorite" figure is able to give a more precise definition of the process of emergence: Let elements (units, atoms, etc.) that have the property "non-P". When a set of such elements exhibits the property P, the property P is - strictly speaking – "emerging".

This figure of "sorite" leads to distinguish between two points of view on collective phenomena : one expressed from the point of view of the individuals; the other expressed from the point of view of the collective.

A. Emergence expressed from the point of view of the individuals

It is based on "action" or "intentionality" of the individuals. Here, we have to distinguish between (A1) the action from several and (A2) the common action with others.

Action from several (A1)

In the first one there is no collective aims or rules, explicit as well implicit: each element follows its own determination or aim. A subsequent issue is that the conditions of this type of collective action are external to the individuals and are not modified by the individuals during their actions. Typical cases are the highway motor driving, the dynamics of financial markets, the free walks of a set of persons on public spaces. Except specific individuals, for example the leaders who personify the goals, the individuals do not play predetermined and dedicated role in the collective action. According to Pierre Livet [Liv94], "the collectives remain virtual", in the sense of "the individuals have any proof or any appreciation, knowledge of the real existence of the collective".

Common action with others (A2)

Conversely, the common action is based on two prerequisites: the definition of a common goal and the acceptation by the individuals to collaborate actively with the others to reach this common goal. Two different sub-cases can be distinguished: (a) when the individuals are (or are not) identified and play explicit role and when they can be unidentified and interchangeable (for example, in space or in time). Typical examples of (a) cases are collective sports (football, basket ball) or social cooperative works. Typical examples of (b) cases are crowd in social public demonstration as strikes. In both, the goal is clearly identified and known by all.

The first case, "action from several", refers undoubtedly to the point of view of modernism: the collective organized figures and patterns that appear are not defined inside the individuals. The individuals are "free" of the collective. Strictly speaking, as defined before, these collective figures are emerging from the set. The second case is ambiguous. Only the first sub-case (a) refers clearly to the Durkheim's point of view : each individual has a precise role in the population.

B. Emergence expressed from the point of view of the collective

It is based on the evolution or the dynamics of the set, they can be analyzed in terms of what we call (B1) symbolic communities and (B2) reactive communities.

In symbolic communities (B1) : The symbolic or deliberative activity (discussions, negotiations, orders, etc.), is a necessarily (even if it is not sufficient) component of the interaction between individuals.

Conversely, in reactive community (B2), the symbolic or deliberative activity is not a necessarily component of the interaction between individuals. In such a case, even if it is not sufficient, the necessary component of the interaction is based on the low level action/reaction principle. In living beings, the instinctive, non interpreted physical sensory-motor interaction between elements (individuals) and the others (others individuals or environment) is of this type.

2.2 About the terms "collective" and "phenomena"

Let us take the case of the human crowds. What is a crowd? Two theories, or two points of view, are confronted. The common point of view, calls "crowd" a sufficient number of human beings confined in a same environment with a density greater than a certain threshold. This definition can be called "a material definition": a crowd is a "thing" or a set of "things". The point of view of the sociologist Gabriel Tarde (1843, 1904) [Tar89], with his famous distinction between the "public" and "crowd' as well as of the sociologist Pierre Livet [Liv94] with his concept of 'communities as virtual" is that a crowd is not a "thing" or "a set of things", but a phenomenon. If we assume, as said before, that a collective is defined by the emergence of a new property, thus it is not sufficient to agglomerate sets of elements to obtain collective features.

As example, a single hair has not the property to be a hair. The collective phenomenon – the relevant and organized collective pattern is " a set of single hair" organized as a hair. It is obvious that all the sets of single hair cannot be a "hair". They can be a "tuft of hair" or other arrangements. Only certain specific sets can be identified as "a hair". That is the same for the piling : a grain of rice has not the property to be a pile of rice. But conversely it is not sufficient to have a lot of grains to have a pile of rice. A pile is a specific class of spatio-temporal patterns with precise structure and precise and specific evolution: symmetric pile, auto-similar growing, surface chaotic avalanches, etc. This means that it is not sufficient to have a lot of elements to obtain a new property leading to collective organization. And far away, when they are, a set *of elements could exhibit several classes of* generic collective behaviors.

That is the basic idea of the assumption " a crowd is not a thing but a phenomenon": a crowd is a specific behavior exhibited by several individuals under some specific conditions. In addition, several classes of collective behaviors can coexist simultaneously. The most relevant of them is the distinction made by G. Tarde between the "public" and the "crowd". Whatever the words used, the addressed question is the distinction between two classes of collective phenomena consistently different: those called by G. Tarde, a "public", as listeners in a concert room and those called a "crowd" as when they are leaving the concert room or when they applauds with the Ola or the recall effects. In the first case of the "public" collective attitude, as in the collective listening, there is a superposition of a crowd effect (the common silent, the common attention) and of an individuated shared behavior (each listening differently of each others). When they are applauding, if we focused on the "Ola" triggering and propagation effect, or on the recall applauding effect with its characteristic periodicity, we focused on the "crowd effect". These last effects are similar of those observed in the public places, as stadium with global motions. They are mainly characterized by an radical loss of individuality in the behaviors. Differently, in the "public" behavior, each individual or groups of individuals can remain more or less distinguishable, resisting to the global behaviors and exhibiting some lack in cooperative attitudes.

2.3 About Modeling Methodological issues

According to these opposite points of view, three main types of methodology of modeling can be distinguished:

• One based on the modeling of a specific phenomenon, called by Lantin [LF97a] and Fleischer [Fle95], "one shot model" : the model tries to model as best as possible one phenomenon (for example : model as best specific turbulences in fluids)

• One based on the modeling of the "things" that produce phenomena, hoping the model could be sufficiently complete to restitute the maximum of the phenomena that the real things produced. Differently than the previous one, this type of model exhibits a new property that is the "generativity". That is usually the meanings of the term 'simulation" on which the simulacrum is expected to have the same level of generativity that the real thing.

• One based on the modeling of the class of phenomena, in the sense of a class of phenomenological invariants.. Instead of the "one shot type model", and similarly with the "real cause modeling", it exhibits the maximum power of generativity. This type of model is situated at an upper level of abstraction of the two first. It supposes to have at disposal a typology of relevant features characterizing classes of observed phenomena. Thus the modeling process aims to model all these features, by previous specification of the classes, whatever the real things that produce these features.

We can observed that :

• the first "object or thing based" definition of the crowd is related to the first attitude of modeling, from which all (i.e. the maximum) of objects' behaviors are expected : individuals, deliberative, reactive ,etc...

• the second "phenomena based" definition of crowd is related to the second attitude of modeling, from which all (i.e. at least the necessary) the relevant features defining a class of phenomena are expected. It needs to pre-specify these relevant features as property of a class to be model by a generative model. For example, in the case of crowd behavior, these features should be: laminar flowing, soft and long-distance avoidance with speed and orientation anticipation (anticipation effect), sudden and short-distance avoidance, merging, jamming, collapses in jamming, flow auto-rerouting, etc.

Let us continue with the example of the crowd modeling. The situation of panic is frequently addressed as one of the main crowd behaviors. Nevertheless, we can notice the state of "panic" addresses more to individual level than the global macroscopic collective level. Indeed, at the collective level, the panic state of individuals could produce several different observed patterns: (1) fluxes running in a same direction, (2) disordered motions like Brownian molecules motions, (3) competitive fluxes forcing in the same direction against others, etc. Conversely these collective figures may appear in absence of panic. We may see these figures as panic effects only when they lead to dangerous situations for the individuals or groups of individuals: (1) when the fluxes are throwing on an obstacle (walls, closed or small doors) (2) unable to find the safe solution, (3) associated with struggle of life. This analysis proves that the term « panic » refers more to the individuals than to the collective.

We can now try to associate sociological concept with types of models and types of effects. For example, the conventional use of geometrical and physical models in Computer Graphics are mainly oriented to the "object modeling". That is also the same in the main conventional use of "agent based model", in the sense that the model is more or less based on the modeling and simulation of intrinsic agent's properties. Conversely, the generic use of genetic or physical algorithms as process applied to simulate "non-genetic or non-physical things", for example to solve optimization problems (parameters' convergence, simulated annealing, etc.) refers more to the abstract approach based on modeling a class of phenomena. Others generic and « effect based » models are models as L-systems or « Cell Programming Language» [Flei95]. We will defend that Physical interacting particle models are of this category.

Figure 1 shows the correspondence between sociological theories, types and contents of models and types of effects.

Sociological concept	**Modeling Concept**	**Emergent effect**
Durkheim's approach Object based "Thing" based	• 3D geometrical modeling (Programming shapes and evolutions Kinematic description, animation functions as trajectories, etc.)	• Defined motions • Non emergent behaviors • No on – line inter-modifications
	• Physical modeling of objects (Programming the dynamics of the "real" bodies(	• Possibility to obtain Emergent behaviors • Non defined motions (implicit definition of the cinematics by the dynamics) • On-line Inter-modifications
	• Agents based models (behavioral models, intelligent agent, cooperative agent, etc.) (Programming the symbolic states of the individuals as behavioral rules and the symbolic interaction between individuals as reactive symbolic rules)	• Possibility to obtain Emergent behaviors • Deliberative or symbolic situations Cultural rules
Tarde's Approach Livet's Approach Phenomena based Effects based	• Cellular automata modeling (including neural networks) • Dynamics systems (including Physical modeling understood as dynamics systems modeling) (Specifying a generic set of behaviors as representing a class of relevant features)	• Emergent motions • Emergent spatio-temporal figures • Non-symbolic Reactive situations

Figure 1. Sociological concepts, types of models and types of effects.

3 Physical modeling

3.1 Philosophical and linguistic issues

3.1.1 Is Physics a science of objects or phenomena ?

It is commonly considered that Physics is more a science of materiel objects than of phenomena. This point addresses the non-trivial relation, between the *phenomenon*, as what it could be observed and what it is accessible, and the *noumemon*, as a possible cause that produces the phenomenon.

During ages, several concepts were

confronted:

• from the radical idealism, sometimes called "critical idealism", defended by the neo-Kantian philosophers for whom the reality - the *noumenon* - does not exist *in itself*, i.e. independently of our representations, and for whom we have access only to the *phenomenon*,

• to the ontological realism which assumes that the science is able to lead to an exact and exhaustive knowledge of the ultimate reality,

• via the Kant's transcendental idealism, which assumes that the reality in itself - the *noumenon* - may exist, even if it is essentially unknowable, and accessible only through the phenomenon,

• or via the objective realism, that is probably the main position of experimental sciences nowadays which assumes that the contingent properties of the universe are not only appearances but intrinsic realities that exist independently of the observers,

• and the theory of Veiled Reality of the Bernard d'Espagnat [Esp95], physicist in Quantum Mechanics, for whom the reality remains intrinsically unknowable in details but the knowledge developed by physics as description of the phenomena, enlightens the structure of a underlying reality.

The two last points of view are quite near to the Kant's points of view, in which the phenomenon is the only object that is observable. Conversely, the *noumenon* is only accessible by "intellectual intuition", as imaging or representation system able to intellectually generate it. That is probably, in our opinion, the best definition of the concept of "model" as a mathematical concept.

Consequently, in agreement with the philosophical fundamentals of contemporary experimental sciences, we can say that physics, and by extension, physical models, are more related to the science of the observed phenomena from which it builds an intellectual (formal, mathematical, algorithmic, etc.) plausible – *realistic* - cause of them.

3.1.2 Physical modeling : two meanings

Usually physical modeling is understood as a system to represent the natural phenomena. That is obviously the case in the experimental science called Physics. But There is a confusion between what it is modeled – the nature, precisely called in ancient Greek "Physis", in the sense of "being done" – and how it is modeled – that refers to a part of "Mathematé" (in ancient Greek) - as the process to study and represent.

We can then remark that there are two meanings of "Physical model":

• a formal representation system with which the nature can be modeled, the "Physis" : we have then to understand "model of physic"

• a formal representation system based on specific properties referred as "Physic" : we have then to understand "physical" as a quality of the modeling system and of the model.

In the first meaning, all the models that are able to represent natural phenomena can be called physical models : for example, in the modeling of physical optical phenomena, we can use geometrical optics (geometrical description) or physical optics (Maxwell equations) and we can observe that the qualitative "geometrical" as well as "physical" points the type of model and not the type of phenomena.

In the second meaning, as arithmetic, geometrical, logic or genetic model, there is any contra-indication to use physical model various type of phenomena (static as well as dynamic).

3.1.3 Properties of Physical modeling as a general formal representation system

Thus, what are the specific properties of a "physical model" as a general formal representation system Let us restrict this theoretical issue in the field of motions. In this field, "Physical" is synonymous of "dynamics", i.e. based on the concept of forces. Notice that, in ancient Greek, "Dynamis" means "force". In the Newtonian point of view based on the action-reaction principle, the force can be seen as a formal descriptor of a correlation between two observed evolving phenomena. To represent dynamic phenomena Newtonian formalism created to dual variables:

• Extensive variables (EV), for example positions or velocities for evolutions in space,

• Intensive variables (IV), as forces called also "influences" before Newton, that describe the correlation between the evolutions of the extensive variables of the two correlated phenomena. Thus, force is the algebraic descriptor of what it is called "interaction", i.e. bilateral influence of two observed phenomena:

the evolution of EV1 influences the evolution of EV2 and vice-versa. The action-reaction principle is an axiom that declares, at the simplest algebra, that these two influences are equal.

Thus, physical modeling can be seen as an abstract representation formal system by which we describe algebraically the dynamic correlation between two (and further any number of) dynamic phenomena, whatever they are, this algebra being based on two dual variables: one (EV) describing the intrinsic evolution of the phenomenon from the influences (IV) of all the others phenomena, and one (IV) describing the mutual influence between each pair of them from the evolution of extensive variables (EV). In this point of view, all the rules that are involved to model a dynamical system is a rule that links EV and IV. These rules can be called Physical rules. We can notice that natural phenomena are obviously represented (modeled) in Physics (Mechanics, Electricity, etc.) by these types of abstract rules.

3.2 Physical particle based modeling as a type of automata cellular network

Referring to the property of Emergence that we placed as a primary property of collective phenomena, cellular networks, as networks of interacting "units", "elements, "atoms" or "cells" are the best candidate to model collective effects in an generative way.

3.2.1 Dynamic automata: the Newtonian Network

From the abstract point of view developed in the previous paragraph, we propose a representation of Newtonian propositions as on networked functional interconnected components. Similarly with the well-known Kirschoff's network in Electricity, a formal physical model for spatio-temporal phenomena will be a network called Newtonian network, composed of two dual components (figure 2): (1) behavioral components and (2) interaction components calculating specific physical rules of correlation (between distances, between velocities). The data that are circulating and exchanged each time between these components are the dual variables: extensive variables (EV) and intensive variables (IV).

- The behavioral component (i) calculates at each time the behaviors according to all their bilateral influences from each others : Fi <-> Xi.
- The interaction component calculates the correlation between the observed resulting behaviors (i, j) : Fi,j <-> R(Xi, Xj) and Fi,j + Fj,I=0

That is why Newtonian formalism is an interaction based paradigm, and should be an excellent candidate to model all the dynamic phenomena mainly based on interactions between behaviors.

To represent dynamic phenomena produced by real systems, the necessary and sufficient basis of elementary components are the three basic rules linking intensive variables and the three basic extensive variables: positions, derivative of the position (velocity) and derivative of the velocity (acceleration), as shown in the figure 2.

Behavioral component of phenomenon (i) : Fi <-> Xi		
d^2/dt^2	Inertial behavior rule of the phenomenon 1 (resp. of phenomenon 2)	$F1=M1*d^2x1/dt^2$
Interaction components between phenomena (i), (j) : Fi,j <-> R(Xi, Xj) and Fi,j + Fj,I =0		
d^1/dt^1	Elastic interaction rule (correlation in distance)	F(1,2)=K*(x1-x2)
d^0/dt^0	Viscous interaction rule (correlation in velocities)	F(1,2) =Z*(dx1/dt-dx2/dt)

Figure 2 – The content of automata components in Newtonian Networks

Each of them can be seen as a small state automata which calculate an elementary differential equations (figure 2). We obtain then a cellular automata network working., in which each cell calculates an elementary differential equations : d^2/dt^2, d^1/dt^1, d^0/dt^0.

The figure 3 is the representation of the Newtonian propositions as a networked automata. We called this representation "Newtonian Networks".

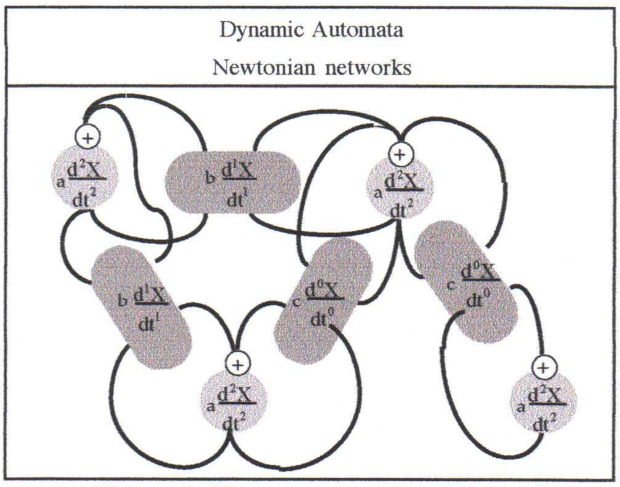

Figure 3. The structure of the Newtonian dynamic automata networks

The circular component (in white) represents the basic behavioral inertial component. It receives the influences, it adds them and it produces the extensive variable. The ellipsoidal components (in grey) represent the interaction component (elastic interaction and viscous interaction). It receives the two behavioral extensive variables that have to be correlated and it calculates the intensive variable that represents the correlation. The basic components correlate the dynamic behaviors in distances and/or in velocities.

Conversely to the differential analytic expression of a complex phenomena, this networked representation allows to represent and calculate easily, non-linear interactions : the modifications, in space or in time of the parameters (a, b, c) allows to represent any kind of non-linearity.

3.2.2 Comparison with others types of Cellular Automata Networks

The following table (Figure 4) sketches the two main types of Cellular Automata Networks : the well know neural networks and the agents based systems seen as networked elementary units.

• Neural network (Figure 4, left) are composed of connected logic automata. The node is the computing elementary element. On each node, all the influences of others nodes are summed according to a weight α for each. To comparing with the Newtonian networks, we identify respectively the inertial lass component, and the interactions components of the Newtonian Networks with the nodes of the neural network and the connections of the neural networks. Newtonian nodes and interactions work. The data that circulate in the network are logic data as in Newtonian networks they are real. Node and connections automata are elementary logic automata. Inertial components and interactions components are differential equations. The elementary components are more complex in the Newtonian network that in neural network. The interaction components can be seen as consistent analogous weighting of influences. In both cases, the influences are summed on the elementary behavioral component.

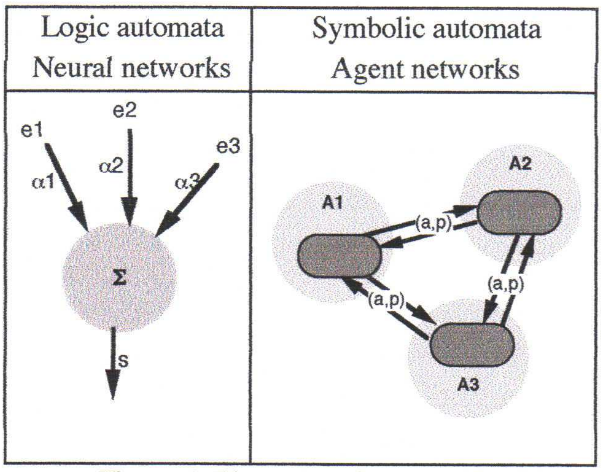

Figure 4. The two main types of cellular automata networks

• In Agents systems (Figure 4, right), the nodes are the agents. They interact through action-perception metaphors. The agent computes the action from the perception. This means that, conversely to neural networks or Newtonian dynamic networks, the correlation between the agent's behaviors is defined "inside the node". The owner rules of the agent interpret the relation between its inputs and its outputs. It is not an interaction symmetrical system. Thus, it cannot implement highly reactive action-reaction principle as in Newtonian networks, because this type of interaction needs symmetrical interaction between agents. Usually, in agent-based systems, physical behaviors are added at a low level to create motions. In the Newtonian networks, in we identify the agent with the inertial element, action-perception metaphors will play through the principles of dual variables: extensive variables can be seen as observed (perceived) variables, and intensive variables can be seen as produced variables, *that will influences the others* "agents". The behavior is based on an elementary differential equation which compute the second order evolution of the behavior, and not an elementary decisional process.

In conclusion, the Newtonian networks (Figure 3) are similar to neural networks. The main differences are in the explicit typing of variables in the first and that the elementary computation are an order complex in the first than in the second. The Newtonian networks are also similar to agents' networks. Both have variables' typing. They differ by the process calculated by units: differential calculation for the *first, other kind of calculation that does not need* symmetrical interaction between agent.

4 Physical particle modeling of emergent crowd behaviors

4.1 State of the art

Numerous works have been published in the area of crowd simulation. They refer to different modeling processes, i.e. different ways for analyzing and understanding the relevant features of collective phenomena.

At the present time, crowd animations can be modeled using three main approaches:

- A kinematic approach, in which key frames and interpolations preset the animation.
- An approach based on agent systems in which agents are managed in real time by rules of behavior defined with automata.
- An approach with a particle-based system where the particles are animated in real time by the application of different forces.

For the kinematic approach, the evolutions of the displacements and of the trajectories are explicitly defined by temporal evolution functions. It attempts to produce the effects without considering their causes: it is *a phenomenological approach.* It takes advantage of the fact that every movement can be rendered, *whatever it is. This method becomes time* consuming when there are many characters that must avoid each other and bypass obstacles. Musse and Thalmann [MT01] automates the determination of trajectories for a group of characters by providing a set of Bezier curves that do not collide. The kinematic approach is *pre-computed and thus totally controlled: this* method is not suitable when the goal is to simulate unpredictable collective behaviors. This type of kinematic model is called by Lantin [LF97] "*one-shot model*". The two other methods are *generative approaches*, describing possible causes that may produce the desired effects. Generative approaches take advantage of the fact that several complex behaviors can be synthesized with a single model; however it is often difficult to find the optimal generic model, if it exists.

Indeed, since crowd behaviors are essentially emergent, generative approaches such as agent *systems or physical models are most appropriate* to reproduce these kinds of phenomena.

Agent models are best adapted to model behaviors with strong individual differentiation, such as cooperative behaviors in which the actors' intentions play a significant role (collective sports, joint action, etc.).

The approaches of Thalmann et al ([MT01], [UT02]), Deviller et al [DDLT02], Donikian *[Don01], or Tecchia, Loscos et al [TLCC01], use* complex finite automata to determine actors' behaviors. These automata represent intelligent autonomous behaviors defined by sets of clever rules. Interactions between persons are modeled by symbolic rules and constraints. When there are many agents, the complexity of the modeling increases considerably. Thus, the number of agents remains usually small, typically insufficient to model large crowds. Agent-models with rules and constraints cannot be adapted to model chaotic phenomena. Dynamic and complex effects are not easily obtained by describing a set of symbolic rules and constraints. Nevertheless, Lantin [LF97], Fleisher [Flei95], Logan [LW94] have modeled self-organizing structures, i.e. complex emergent structural effects, using similar approaches for the simulation of the growth of living organisms.

Reynolds [Rey87] has addressed the modeling of emergent collective phenomena by agent-based systems. He extended this work by adding a metaphoric steering motor force to the agent-particles [Rey00]. Goldenstein [GKM01] use a similar agent-particle system with different collision detection and path finding techniques.

In the case of collective emergent behaviors such as in crowds, the basic phenomenon is *mutual, implicit, non-conscious and non-*

deliberative adjustment, in which global and external dynamic effects are more prevalent than steering or deliberative cooperation. In this mechanism of adjustment, collisions and avoidance are included implicitly. this mechanism may be simulated with physically-based particle models incorporating two elementary repulsive forces. This type of physical model is largely used today to simulate the phenomena of traffic jams [Nag96] or sand heap dynamics [LHM95].

Particle modeling has already been used by Bouvier et al [BG96] to simulate crowds, even though it was not used here to regulate the dynamics of avoidance and anticipation.

4.2 Specification of class of dynamics effects

In the method proposed here, to use physical models to model features that are relevant for classes of phenomena, the main difficulty is the specifications of these features. In the field of collective behaviors, no sufficient specifications exist nowadays.

The main observed phenomena developed for controlling motorway traffic or for the safety of public spaces (stadium, rail stations, etc.) are usually: short-distance avoidance, jamming, flowing with processions, chaotic dispersion. To compensate this lack of knowledge and categorization by providing by ourselves plausible observed categorizations, we added:

• Medium-term or long-term distance avoidance, with anticipation effect in trajectories and in velocities (long distance small trajectory rerouting, slowdowns / acceleration)

• Jamming, with internal sub-groups collapses and unpredictable border flowing

• Propagation effects as the Ola effects,

• Flow penetration and mixing,

• Global flows' interaction, with flow laminar rerouting, curls and vortices.

• Velocity coordination and spatial coordination: step adjustment, psychological compressibility, psychological incompressibility threshold.

4.3 Crowd emergent effects simulation by means of Newtonian Networks

According to the sociological point of view presented before, a set of units leads to a crowd behavior by losses of individuality. As last examples of such a fact, in a choral, the individuals properties of voices as vibrato have to be removed as more as possible, to avoid cacophony. And in the queue, individuals' behaviors are risky for all the other individuals. More the individuality of unit is, more impossible will be the collective non-deliberative organization.

4.3.1 Unit (or characters) modeling

Thus, it should be sufficient to model the set of persons by a set of similar units. In our particle model, the elementary unit being punctual inertia, we model at the simplest level, characters as punctual inertia, which calculate positions, through acceleration provided by the sum of forces (influences).

4.3.2 Interaction between units :

All these units are in bilateral automatic interaction, according to the action-reaction basic principle, to regulate the correlation between their behaviors. Two complementary interactions should be sufficient:

• *Family of correlations in distance* (Figure 5 left), commonly called "elastic effects" or potential interaction. Thee general form is given in the following table (on the left). They will be able to regulate:

- The spatial correlation between individuals: attraction, repulsion, cohesion, etc...

- The immaterial psychological volume with dynamic properties as non-penetration, psychological observed elasticity and compressibility (resp. rigidity or incompressibility)

- Automatic avoidance with short-distance, medium-distance, long-distance anticipation

• Family of correlations in velocities (Figure 5, right), commonly called "viscous or friction effects" or viscous or friction interaction. They *can be represented, in the most general case* by finite state automata, as shown in the following table (on the right). They will be able to regulate correlations as :

- Effect of anticipation on the velocities during the avoidance process (slowdowns before the encountering, re-acceleration after

- adjusting velocities (walking at the same steps, etc.)

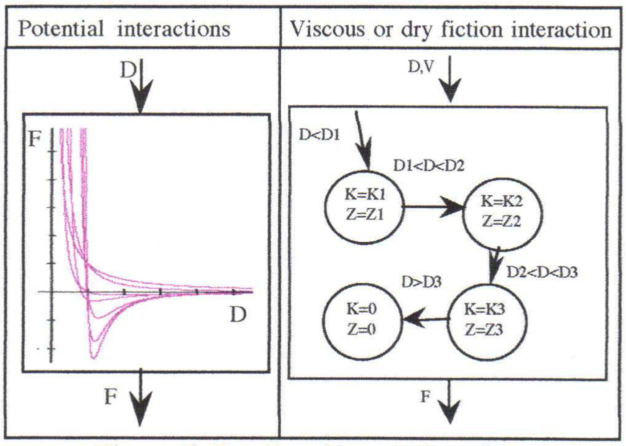

Figure 5. Family of interactions between characters

4.3.3 *Obstacles modeling*

The obstacles are modeled as persons by punctual masses or set of punctual masses. The obstacles are "things" that dynamically restrict more or less the configuration space and that work against motion. They can be fixed or mobile material objects, but also immaterial things as sunny and warm areas, winded area, and finally combination of material object and immaterial things. For example, a fountain has to be modeled as an evolving zone including the fountain itself and surrounded by zone of dispersed water. The "brume" will be cold in winter and it will be an obstacle to be avoided. But in summer, it will become a fresh and pleasant zone, that should to be not avoided.

4.3.4 *Characters/obstacle interaction modeling*

The interaction between obstacles and characters are modeled from the type of interaction functions. For example, wind will work against characters' motion as others characters flows.

4.3.5 *Elementary intention to move*

The only minimal autonomous rule we have to implement in the characters is the elementary intention to move. For the first experiments, it could be implement by means of : attractive or repulsive external targets, initial velocities, injecting process that inject some characters in the confined expected environments with a specific initial localization, and/or initial density and/or initial velocities.

4.4 Results

The snapshots of simulations presented at the end of the paper show the obtained collective phenomena. To facilitate their observation, we have to use several types of visualization: (1) points that reveal more the absolute and relation localization, (2) parts of trajectories that reveal more the dynamics of the avoidance, of figures of flowing, etc and (3) humanoids with which we will compare better with human crowd observations.

4.4.1 *S1 : Simulations of sparse individuals with low density*

We can observe dynamic automatic avoidance with several distances of anticipation.

4.4.2 *S2 : Simulations of meeting of two dense flows in a straight road*

We can observe three main dynamic phenomena :

- Constitution of a blocking jam
- More or less infiltration with internal curling rerouting of individuals

4.4.3 *S3 : Simulations of meeting of two very high dense flows in a straight road*

Increasing the density, increase the collective organization: less infiltration of the two groups, global rerouting of flows with important curls and vortex at the cross point.

4.4.4 *S4 : Simulations of meeting of three dense crossing in a square*

It appears three main relevant phenomena:

- Constitution of files and queues
- Global laminar rerouting of the flows with vortex at the cross point

4.4.5 S5 : Simulations of compact flow thrown on a fixed small obstacle

Notice the laminar flowing during the avoidance.

4.4.6 S6 : Simulations of flow attracted by a fixed large obstacle

The observed phenomena are different than in S5. We observed all the figures of auto-similar and chaotic well-formed packing, as those that appear in granular materials:

• Constitution of a well-formed pile (symmetrical as in granular materials)

• Constitution of sub-groups (observed in the animation)

• Chaotic escapement on the boarders of the pile

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